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Interstrand Contact Resistance of Nb_3Sn Superconducting Cables Extracted from Magnets

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Abstract

This paper is a report about measuring the Interstrand Contact Resistance (ICR) of the superconducting Rutherford-type cables that Fermilab is implementing in the High Field Magnets made of Nb_3Sn strands. The measurement is performed at cryogenic temperature (4.2 K), and requires the use of a high-sensitivity low-noise acquisition system. The magnitude, knowledge, and control of the contact resistance between strands in a cable are important factors on the performance and design of the magnets.

Introduction

In 1911, Heike Kamerlingh Onnes, a Dutch Physicist, discovered superconductivity. During his conductivity experiments of metals at low temperatures, he discovered that the resistance of a mercury sample dropped to an immeasurably low value just at the boiling point of liquid helium [1]. He called this phenomenon superconductivity. A characteristic of a superconductor is an immeasurably low resistivity, so that current can flow in a sample without dissipation. They are used to produce high magnetic fields up to a certain limit (depending on material, temperature, and current) called the critical field.

The discovery of superconductivity has led to many applications such as superconducting magnets. Magnetic fields are used extensively in high-energy physics research to bend, focus, manipulate, and analyze the beams of energetic charged particles that are used to investigate the fundamental structure of matter. Controlled thermonuclear fusion is using magnetic confinement of very hot deuterium-tritium plasma to commercially produce power through fusion [2]. In a MRI (magnetic resonant imaging) machine, a radiofrequency pulse of magnetic field induces protons in the patient to process in the direction of the static magnetic field supplied by the superconducting magnet. The development of functional magnetic resonant imaging enables one to locate some sites in the brain that are involved in body function or thought. Applications of this technique include mapping the brain and preoperative surgical planning. These are only a few ways that superconducting magnets are aiding in the advancement of science, medicine, and technology.

There are two types of superconductors, Type I and Type II superconductors. Lead, mercury, tin, and aluminum are Type I superconductors. They do not admit a magnetic field in the bulk material and are in the superconducting state provided the applied field is below a critical field that is a function of temperature. Superconducting alloys like lead-indium, niobium-titanium, and niobium-tin are Type II superconductors. Type II superconductors are characterized by two critical fields, B_{c1} and B_{c2}, which are both temperature dependent. For fields $0 < B < B_{c1,}$ the superconductor is in the Meissner phase with complete exclusion of the field from the interior [1]. At fields $B_{c1} < B < B_{c2}$, Type II superconductors will permit magnetic fields and currents through the bulk material.

The most commonly used Type II superconductor is NbTi because it is ductile and easy to produce in large quantities. However, Nb_3Sn has higher performance than NbTi. At a constant temperature of 4.2K, Nb_3Sn can operate in a magnetic field up to 21T. NbTi, on the other hand, has a maximum operating field around 11T. The non-copper critical current of Nb_3Sn can be up to 3000 A/mm^2 at 12T 4.2K, while the best NbTi is about 2000 A/mm^2 at 6T 4.2K [3]. On the other hand, NbTi is a malleable alloy while Nb_3Sn, which is an intermetallic compound, is so brittle that it will fracture at elongations of about 0.3%. Therefore, Nb_3Sn has a much better performance, but it is difficult to use because of its brittleness.

Fermilab's HFM (High Field Magnet) program is designed to develop the next generation of superconducting accelerator magnets with high operating fields and margins for different applications. Possible applications of HFM include superconducting magnets for the Tevatron, for a future very large hadron collider, and for beam transfer lines. Another possible application is for second-generation LHC IR dipoles and quadrupoles with larger apertures and higher operating margins for higher luminosity.

The goal of the experiment described in this report is to measure the Interstrand Contact Resistance (ICR) of the superconducting Rutherford-type cables that Fermilab is using in High Field Magnets made of Nb_3Sn strands. The measurement is performed at cryogenic temperature (4.2 K), and requires the use of a high-sensitivity, low-noise acquisition system. The magnitude, knowledge, and control of the contact resistance between strands in a cable are important factors on the performance and design of the magnet. Values too large may compromise cable stability. On the other hand, values to small may compromise field quality and give excessive eddy currents, currents induced in metals by change of magnetic field.

In order to take these measurements, a sample must be prepared by soldering current leads to strands at opposite corners of the cable's cross-section and voltage taps to strands on one face of the cable. The voltage distribution across the cable cross-section at a fixed current should be analyzed in order to evaluate the resistance at the contact points among strands. The resistance at the contact between a strand and those on either side of it is called "adjacent resistance", Ra. The resistance at the contact between a strand and those that it crosses over is referred to as the "crossover resistance", Rc.

For the measurement of contact resistance in a cable, current leads are attached to strands at opposite corners of the cable, shown below in figure 1, and the voltage drop from the negative current lead to a given strand is measured. The results from this type of measurement should match one of the following plots shown below in figure 2.

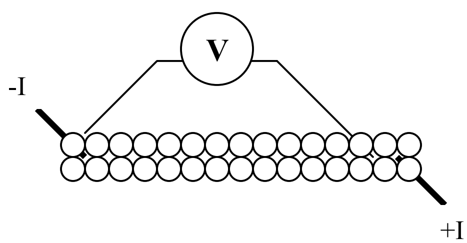


Figure 1. Voltage tap measurement

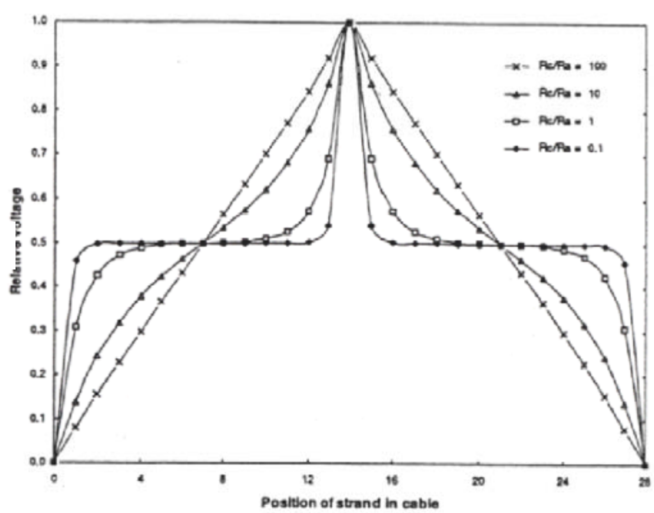


Figure 2. Voltage vs. Strand

Experimental Set-up

The set-up for the experiment was assembled using the following equipment:

- Cryostat
- Nanovoltmeter & Scanner (7 channel max)
- Power Supply (maximum current = 100A)
- Computer and LabVIEW® program

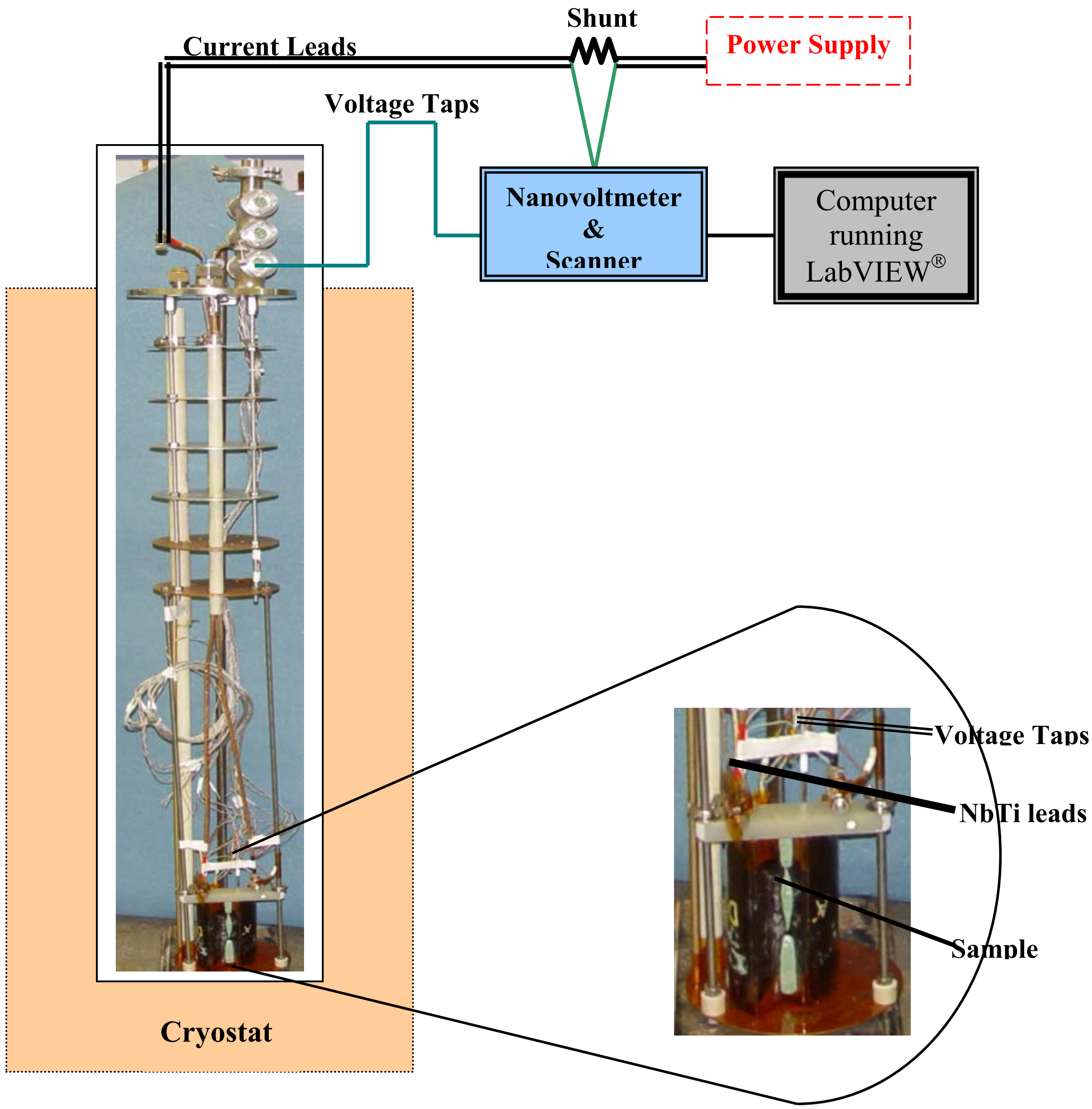


Figure 3 Apparatus Set-up

Figure 3 shows the sample holder inserted into the cryostat. Using this sample holder, data can be taken from upto five samples. All voltage taps from a sample were wired to the same connector on the cryostat flange. Each sample could be measured by connecting the nanovoltmeter scanner to its connector.

The current leads coming from the sample were NbTi strands with copper wires connected in parallel (in the event of the NbTi quenching). Voltage taps were connected at each end of the NbTi leads to monitor the voltage drop and to detect quenching. These NbTi leads were connected to copper wire leads that went from the inner chamber of the cryostat to the outside. The copper leads on the outside were then connected to a power supply. Indium was placed between all contacts from the NbTi wires to the power supply to achieve a good electrical contact.

Current is brought to the sample, from the 100-A power supply, through two copper leads and NbTi superconducting strands. The current circulates through a shunt resistance, which allows for a precise current measurement. Indium was also placed between all contacts with the shunt. A pair of potential taps was connected from the shunt to the nanovoltmeter so that the current could be recorded during testing.

Test Station

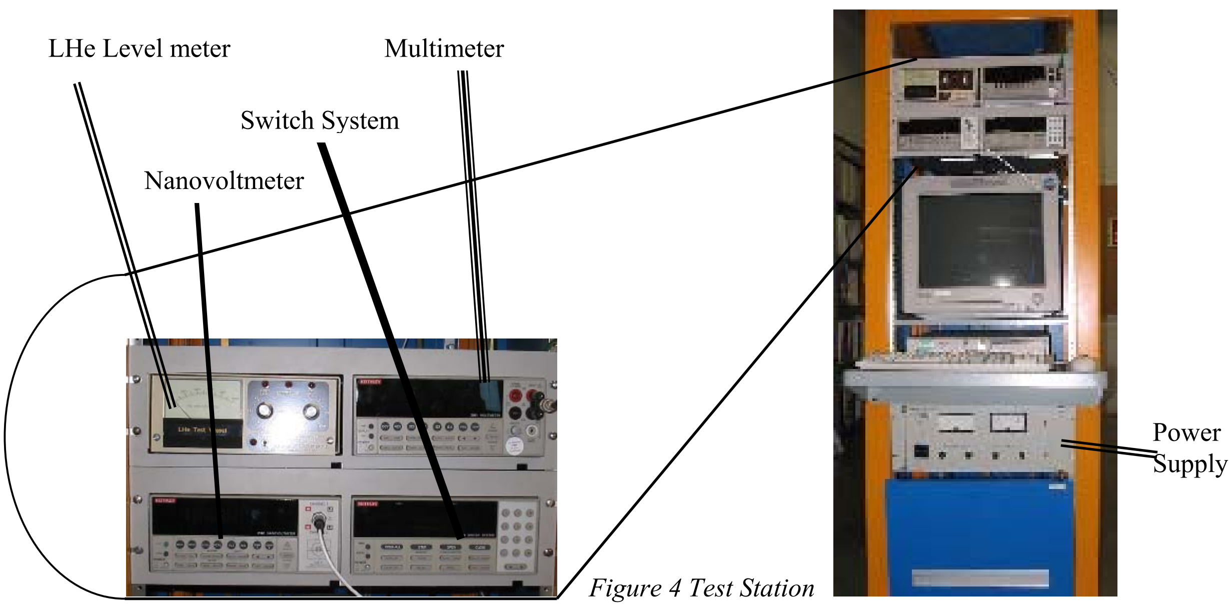


Figure 4 Test Station

Figure 4 shows the test station that is used to acquire data from the samples. The test station has been retrofitted with a multiplexer (Keithley 2001 switch system with a 7168 nanovolt scanner) and a digital voltmeter (Keithley 2182 nanovoltmeter). This system allows measurement at a fairly fast rate (about one sample every 50 milliseconds) of eight channels. Seven channels measures the voltage taps and one channel measures the voltage drop across the shunt.

The multiplexer and the nanovoltmeter are remotely controlled through a PC with LabVIEW® acquisition software. The scanner can be used to read the signals of any sample by connecting it to the appropriate connector. An advantage of this new system is the light mass to be cooled at 4.2K, which allows for less helium consumption and contributes to reducing the voltage drift during measurement. With the previous apparatus all the liquid helium was spent in about two hours. With the new apparatus it lasts for more than six hours.

Sample Preparation

The samples tested were extracted from coils and instrumented with several voltage taps. These samples were prepared according to the following procedure. A section was cut from the coil straight section. This section was reduced to the final length (10 mm longer than a transposition pitch) by removing 25 mm from each end. These last two cuts were performed with a wet saw taking particular care not to "open" the ends of the sample (for instance some samples were cut after immersion in liquid nitrogen). The ends were carefully polished in order to avoid contacts among strands by residues from the cut. Epoxy and insulation were removed from a 10-mm long section at the end of the cables to be tested. In this area, current leads were soldered to two strands at the edges of the cable [4]. Because of the transposition angle a strand of these lies on the bottom side of the cable. Therefore 6 mm sections of some strands above it were removed and the lead (NbTi wire) soldered.

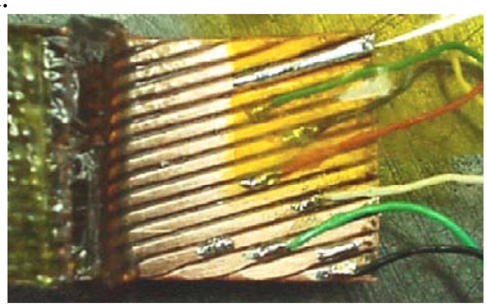


Figure 5. Sample with voltage taps and isolated strand

Voltage taps were soldered on selected strands: those to which the leads were soldered and 6 additional strands. Two techniques were alternatively used in order to prevent bonding adjacent strands during soldering of leads or voltage taps: the target strand was isolated from the adjacent by a U-shaped thin layer of Kapton, or the adjacent strands were protected by insulating varnish and masking tape.

Measurement Procedure

Measurements were performed in boiling liquid helium at atmospheric pressure. The current was ramped from zero to the set value in a few seconds, held for about 30 seconds and then turned off to zero. This procedure was repeated for several different current values, first increasing the set point by steps of 20 A, up to 100 A, and then decreasing it (i.e. 0, 20, 0, 40, 0, …100, 0, 80, 0…). This full set of measurements was repeated one or more times in order to check reproducibility (sometimes with different current steps).

The use of a stepped current profile was preferred to the slow constant increment used by other authors [5] because it allows for a more precise correction of the voltage offset at zero current.

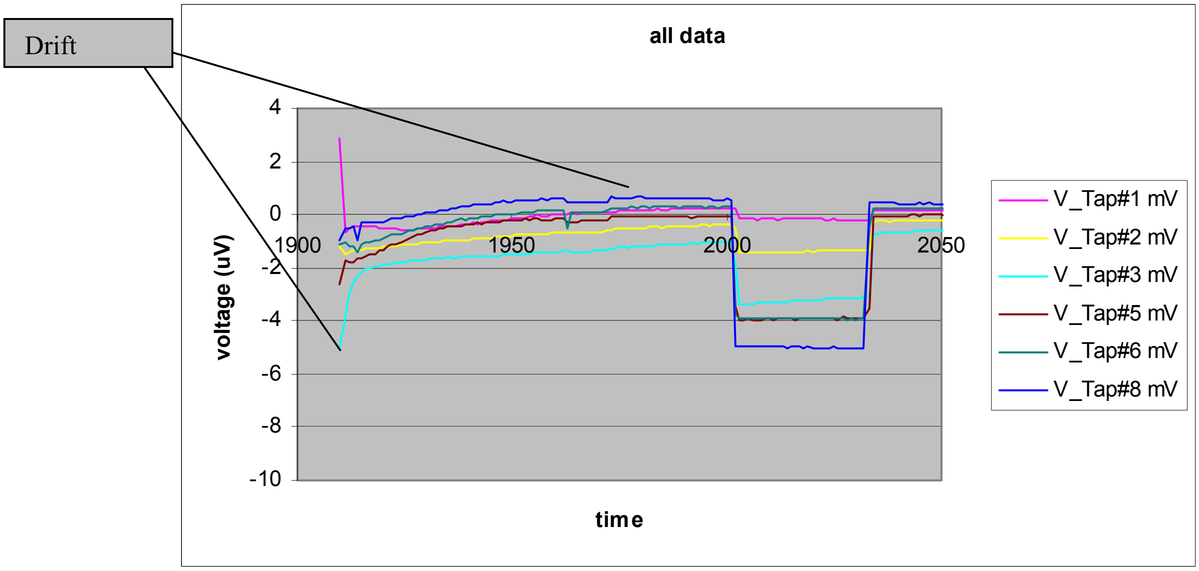


Fig. 6 Chart Showing Drift of the Voltage

Typically this offset was drifting of about 2.8μV during the first minutes after changing the connector (possibly because of the different temperature of the two parts of the connector). No measurements were performed during this transition time. After this transition the drift was less than 0.15μV. Data collected during ramps and in a few seconds following were discarded to avoid transient effects. Measurements of voltage versus current were linearly interpolated to obtain the resistance between the strands connected to the leads (R_{TOT}) and the resistance from the negative lead to each instrumented strand [4].

Procedure for Data Analysis

The goal of the data analysis is to obtain the voltage distribution across the cable cross-section when a constant current (for instance 100 A) is flowing from one edge of the cable to the other. The voltage of the instrumented strands is measured at several currents and a linear interpolation is used to obtain an effective resistance. This method is used in order to reduce the noise and to see if deviation from linearity occurs above a current threshold. The voltage distribution (at fixed current) obtained in this way is compared with a simulated voltage distribution (using VIRCAB [4]). The main cable parameters (strand and cable dimensions & strand number…) and guess values for Ra and Rc are used to generate the simulated voltage distribution. The guess values are changed until a good fit of the experimental data is achieved. In the following all steps of the data analysis are described in details:

- Make a duplicate chart of the data besides the original data.
  - All of the changes will be made to the duplicate chart.

- Collect all data regarding the same sample in a separate file

❖ Multiply each cell of the Shunt Ampere column by 1000. (Volts → Amps)

❖ Make an XY scatter plot of shunt (A) vs. time. (Fig. 7)

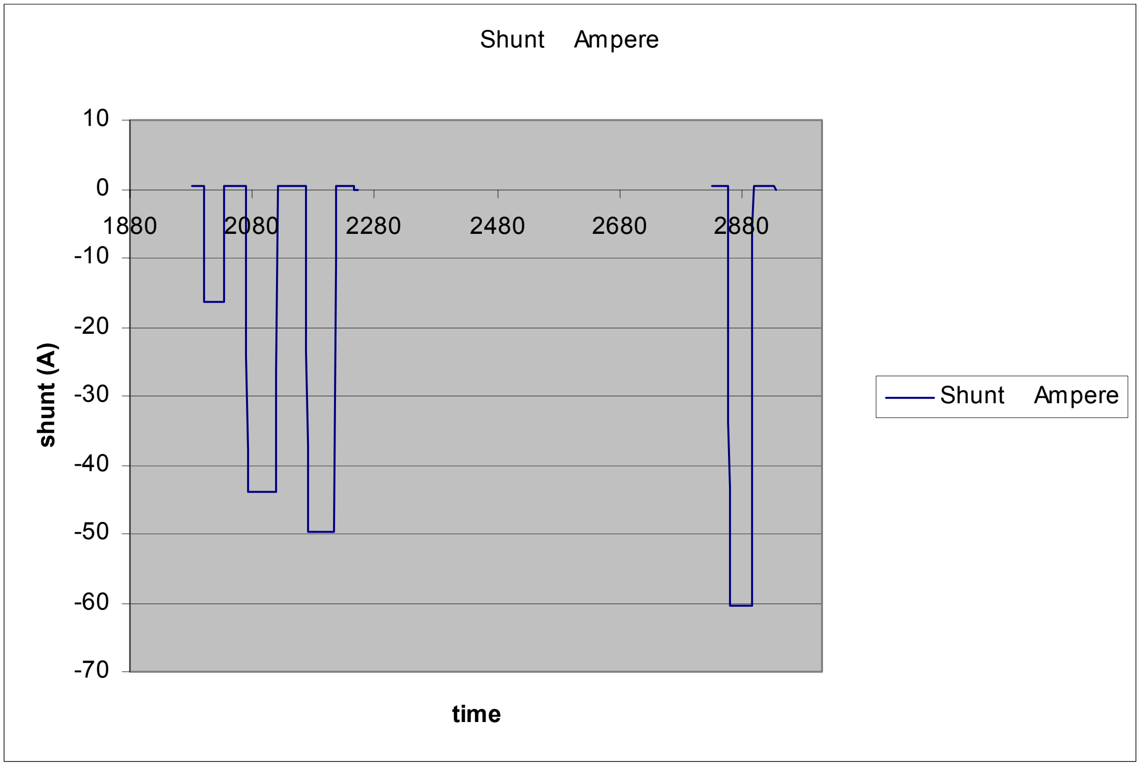


Fig. 7

❖ Delete the rows and/or columns of data that corresponds to noise and/or faulty voltage taps from the chart.

❖ Multiply all Voltage Tap Columns by 1,000,000. (Volts → Microvolts)

❖ Now make another chart of All Data with an XY scatter plot of voltage (μV) vs. time.
  ➢ Do not include the shunt.

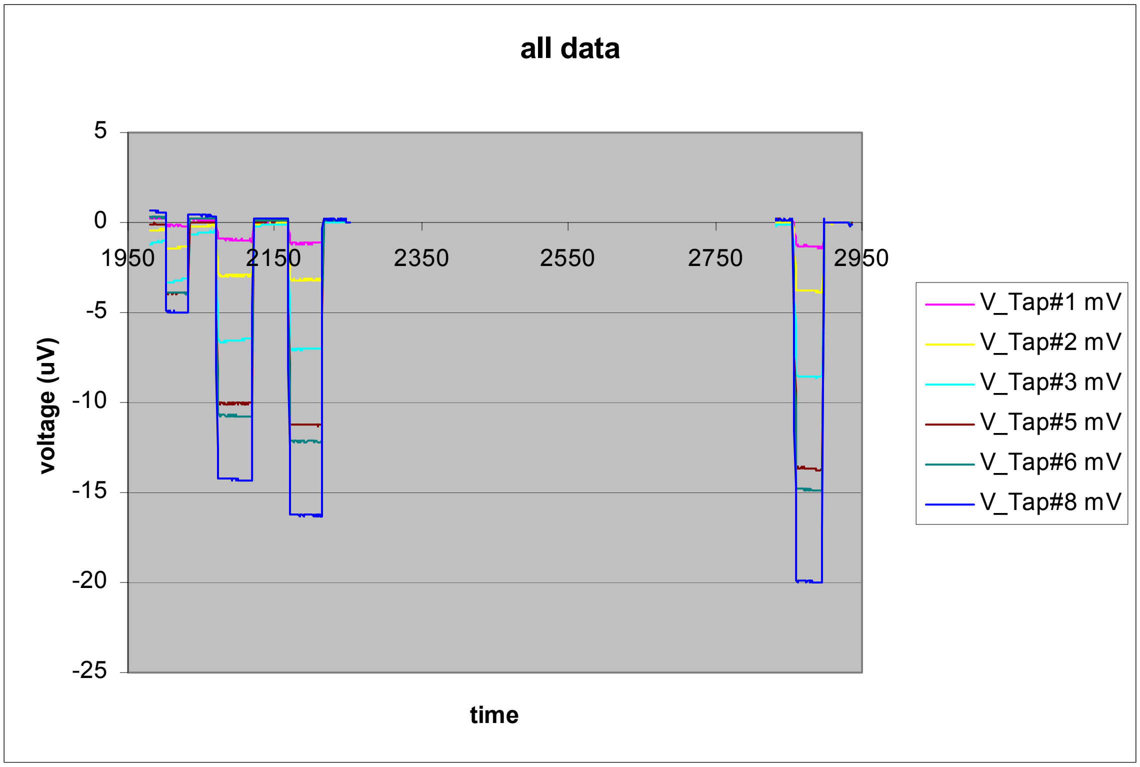


Fig. 8

- Reduce the offset of the Voltage Taps.
  - After making the chart, zoom in the graph along the x-axis to see where each of the Voltage Taps can be offset to zero.
    - Find the time when the drift is over (T0).
    - Subtract from all the other times the value of the Voltage Taps at time = T0.

- If there is any more noise or drift delete it.

- Paste all of the good data in the Analysis spreadsheet in its appropriate column.

- Find the Averages by using the flat horizontal lines from the All Data chart.
  - Using the line without current, use about the last 10 data points at the end of the line to find the average**.**
  - Using the line with current, use all of the data of that line for the average.
  - <u>Be careful not to include any data when the current is changing</u>
    - The lines with current can be notified by creating a gray bar by using gray to shade in the row.
      - This gray bar is the most important data.

- Find the Signal from the gray rows by using the averages, from the analysis sheet.
  - In order to find the signal, a cycle in the graph must be found from the data.

- The average without current before current is A. The average with current is B. The next average without current is C.
  - In the analysis sheet, the average on the gray bar is B. The average above the gray bar is A. The average below the gray bar is C.
  - Now use the formula B - (A + C) / 2 to calculate the signal.
- Do this for the shunt and each one of the voltage taps.

- Make a summary table of the voltages of each strand using the signals from the analysis sheet. (Table 1)

Summary table - VOLTAGE DROP on each strand							
	Ch 1	Ch 2	Ch 3	Ch 4	Ch 5	Ch 6	Ch 8
Δ Current	Strand 15	12?	10?	7	5	3	
A	μV	μV	μV	μV	μV	μV	
16.92767	0.351311	1.107305	2.459083	0	3.870721	4.16402	5.463535
44.4443	1.023613	2.834609	6.248619	0	10.08591	10.91306	14.5649
49.96124	1.161649	3.161179	6.987147	0	11.29156	12.2362	16.40644
60.96609	1.354237	3.810609	8.518744	0	13.74134	14.90279	20.02073

Table1

Compute the effective Resistance

- Using the summary table, Voltage Drop on each strand, make another XY scatter chart of Current (A) Vs. Voltage (μV). (Fig. 9)
  - Add linear trendlines to each set of points.
    - Set intercepts = 0 and display equation on the chart. (This is the effective resistance)

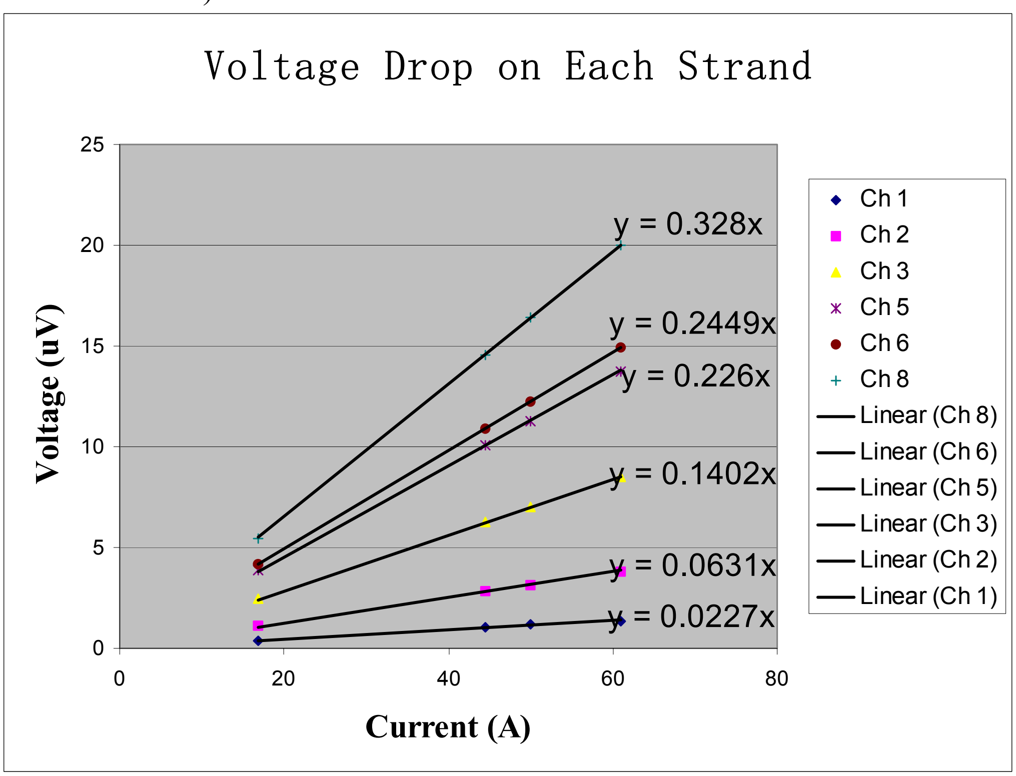


Fig. 9

- Finally, after completing the chart make another summary table of the Effective Resistance.

EFFECTIVE RESISTANCE computed by linear interpolation						
Ch 1	**Ch 2**	**Ch 3**	**Ch 4**	**Ch 5**	**Ch 6**	**Ch 8**
2	**4**	**6**	**8**	**10**	**11**	**15**
μΩ	μΩ	μΩ	μΩ	μΩ	μΩ	μΩ
0.0227	**0.0631**	**0.1402**	**0**	**0.226**	**0.2449**	**0.328**

Table 2

- Cut and past this table into the Fit with VIRCAB sheet.
  - Make sure the Voltage Measured and the strand column coincides with the Effective Resistance table.

- Make a guess of the values to be used for the crossover and adjacent resistances.
  - Place those numbers in the figure below in the green.

- Look in the Fortran folder under C: (Fig. 10)
  - This figure below is Vircab.inp

```
'c:\fortran\vircab\vircab.res'           'Main results'
'c:\fortran\vircab\vircab.rrr'           'Only Nb,V values'
'c:\fortran\vircab\vircab.ras'           'Ra-values'
'c:\fortran\vircab\vircab.rcs'           'Rc-values'
28,28,2                   'NBMi, NBMa, NBSt: NUMBER OF BANDS'
1                         'NDiRa: 0=RANDOM, 1=LINEAR RANDOM'
3.2D-6,0.D-6             'RaMe1,RaVa1 (Ra on edge 1) (Ohm)'
3.2D-6,0.D-6             'RaMe2,RaVa2 (Ra on edge 2) (Ohm)'
1                         'NSpRa (do not change)'
1                         'NDiRc: 0=RANDOM, 1=LINEAR RANDOM'
200.0D-6,0.D-6             'RcMe1,RcVa1 (Rc on edge 1) (Ohm)'
200.0D-6,0.D-6             'RcMe2,RcVa2 (Rc on edge 2) (Ohm)'
1                         'NSpRc (do not change)'
1.D-18                    'RsCon: Constant Rs value (Ohm) (do not
change)'
100.                        'CurM: Measuring current (A)'
1                    'NStrP: Strand with positive input current (usually
1)'
15                   'NStrN: Strand with negative input current (usually
NS/2+1)'
28                        'NS: number of strands (only even numbers)'
.0142                      'h: width cable (m) .0142 for cos-theta
.01507 Racetrack'
.11                       'TPStr: cable pitch (m)'
1.D0                      'One (do not change)'
0                    'kAdRem: Adjacent strands removed (1) or not (0) (do
not change)'
1.D-1                'RaRem: Ra of a removed strand'
1.D-1                'RcRem: Rc of a removed strand'
0                    'kStrip: Insulating strip inserted (1) or not (0)'
0.0001                    'RcStri: Rc of an insulating strip'
```

Fig. 10

- After making the changes to the input open Vircab.exe
  - Wait for the output data to be changed.

- Open Vircab.res to see the results.
  - Copy the necessary data under the section (`Voltages (in µV) per strand over the cross-section)`.
    - Paste the data on the Fit with VIRCAB sheet in the VIRCAB results column.

- If there are some minor problems with graph change the scaling factor based upon the change in the ratio.
  - Repeat adjusting the Ra and Rc until the chart has a good fit.
  - The values that give the best fit are the results.

- This is an example of a complete chart.

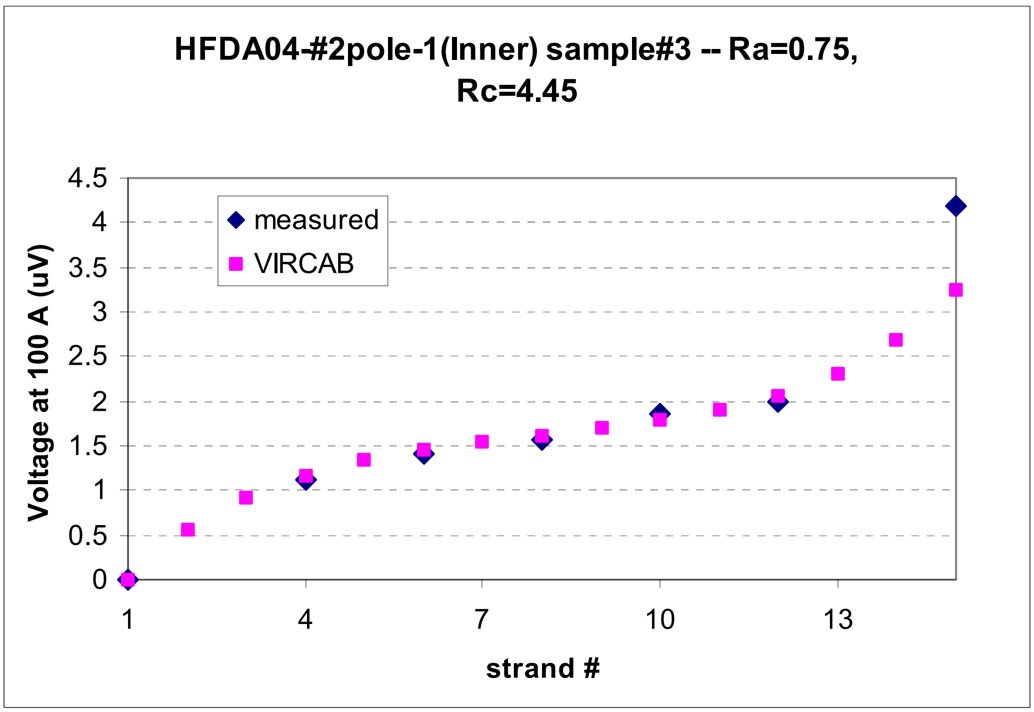


Fig. 11

Sample Description

All cables tested were made of wires produced by Oxford Superconducting Technology using the Modified Jelly-Roll fabrication method. They had 54 sub-elements surrounded by a Nb barrier [6]. The first sample was a five-inch (127 mm) long section of the straight part of a coil of HFDA04. The HFDA-04 magnet is a cos-θ magnet fabricated with the Wind-and-React technology using the ceramic binder and cable 28-1-No. The cable parameters are presented in Table 3. All four cables on the pole-1 turns were instrumented and tested (Fig. 12). The technique used to instrument the cables is described in [7].

Figure 12

TABLE 3: Cable parameter

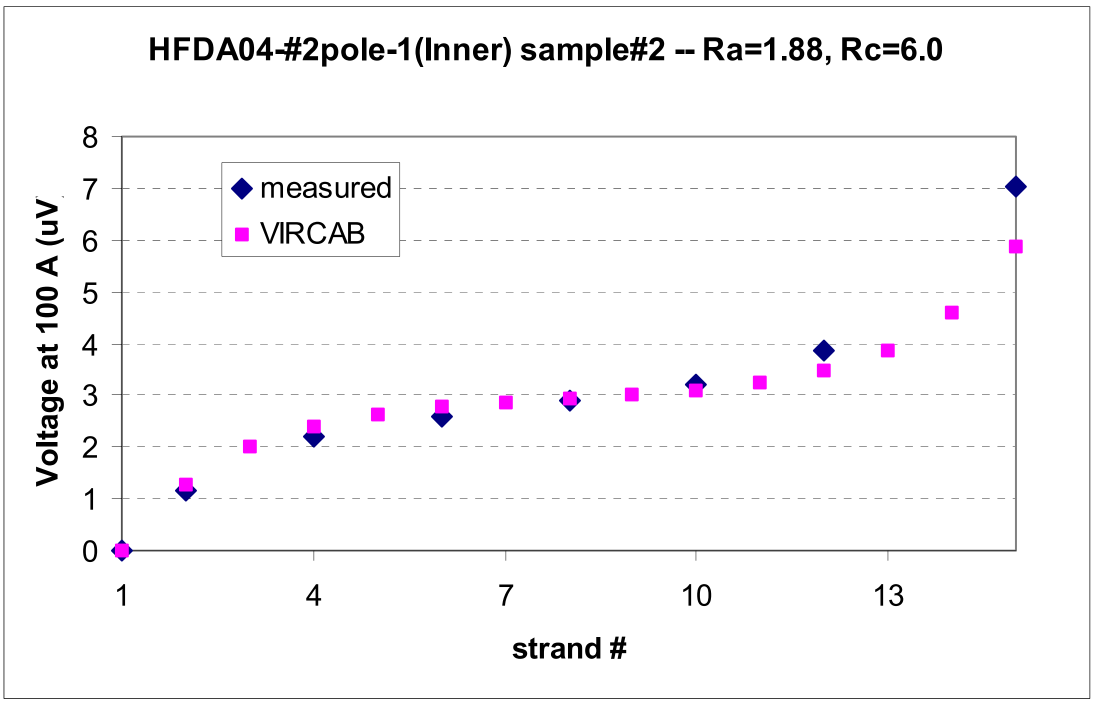
	HFDA04-02	LBL
Cable	28-1-No	28-1-No
Strand diameter (mm)	1	.8
Number of strands	28	26
Cable width (mm)	14.23	11.34
Cable thickness: thin-thick edge (mm)	1.69-1.91	1.407
Cable pitch length (mm)	110	81.28
Stainless steel core thickness (μm)	No core	No core

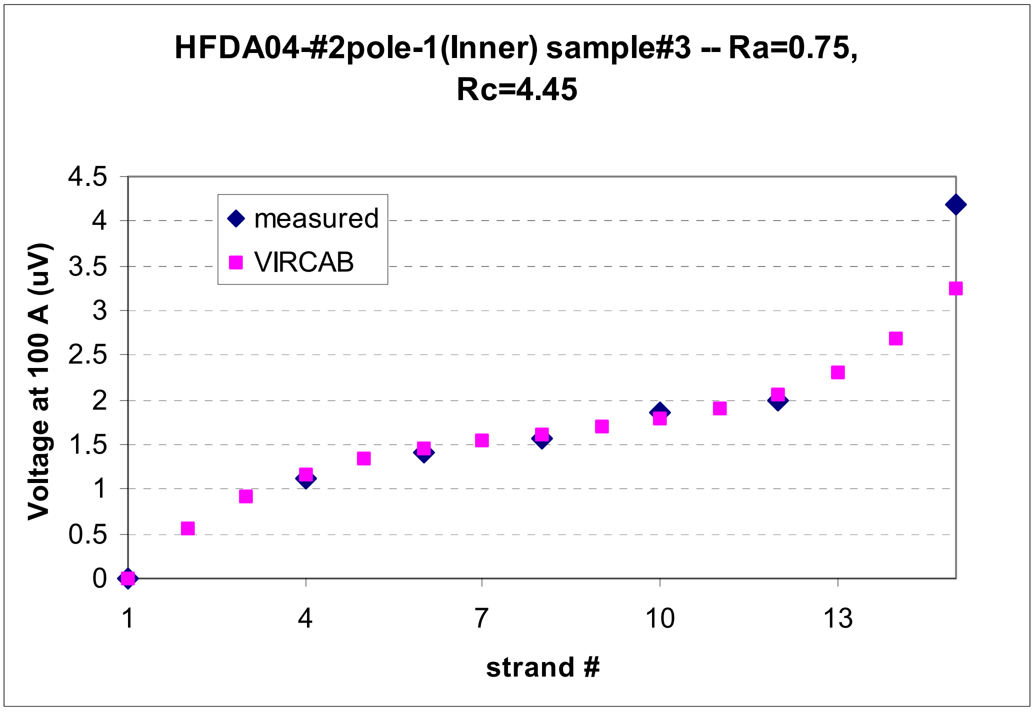
The second sample was cut from the straight section of an outer coil of the LBL magnet RD3A. All cable parameters are shown in Table 3. The cables tested were on the innermost and outermost turn of the coil (double pancake).

Results

The following charts display the voltage (scaled at 100A) of the instrumented strands on all cables tested. They also show the best fit obtained using VIRCAB. The Ra (adjacent resistance) and Rc (crossover resistance) are the only true parameters of the fit. The values producing the best fits are reported in each chart below. The LBL sample was measured twice in order to double-check the results given from the first test. In the first measurement, Sample #3 showed a non-linear behavior of voltage versus current. Sample #3 was close to sample #4, which had a large dissipation due to a poor splice. Thermal or mechanical changes on sample #4 at high current may have affected the measurements on sample #3.

HFDA04-#2pole-1




HFDA04-#2pole-1(Inner) sample#3 -- Ra=0.75, Rc=4.45
measured
VIRCAB
Voltage at 100 A (uV)
strand #
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
1
4
7
10
13

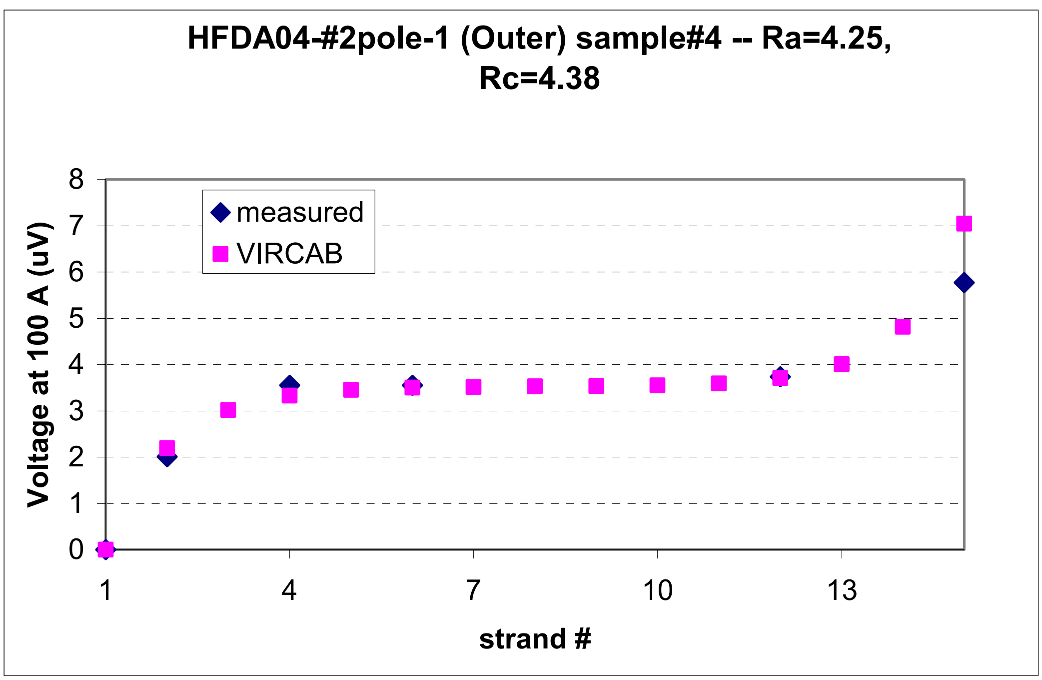
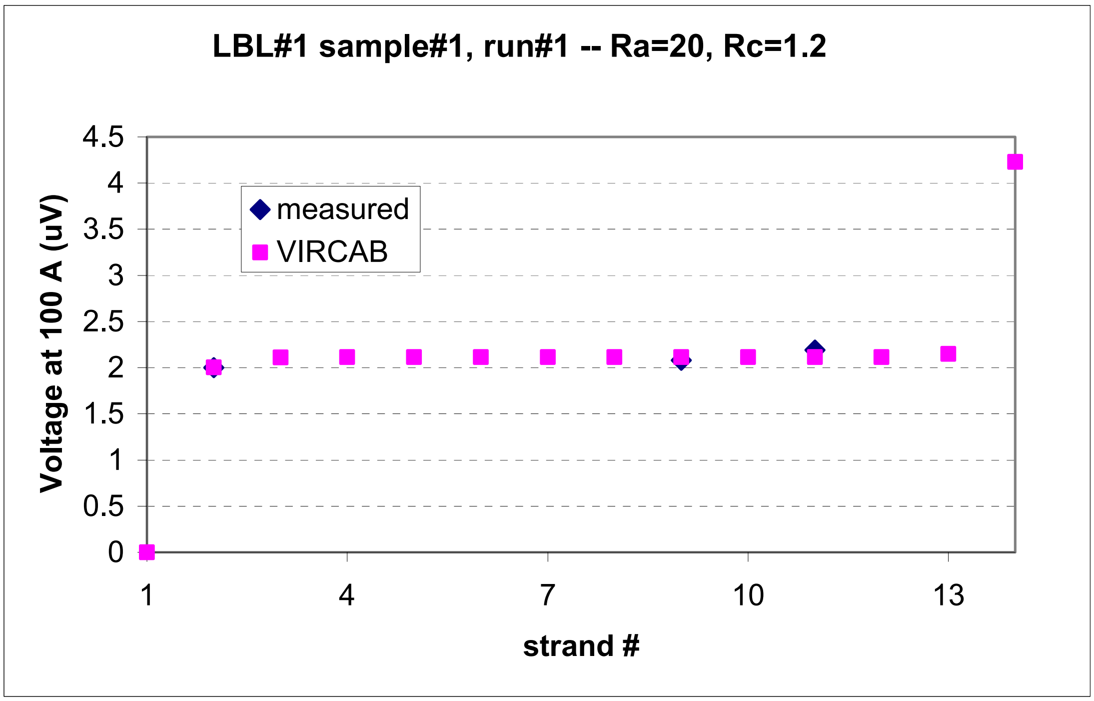
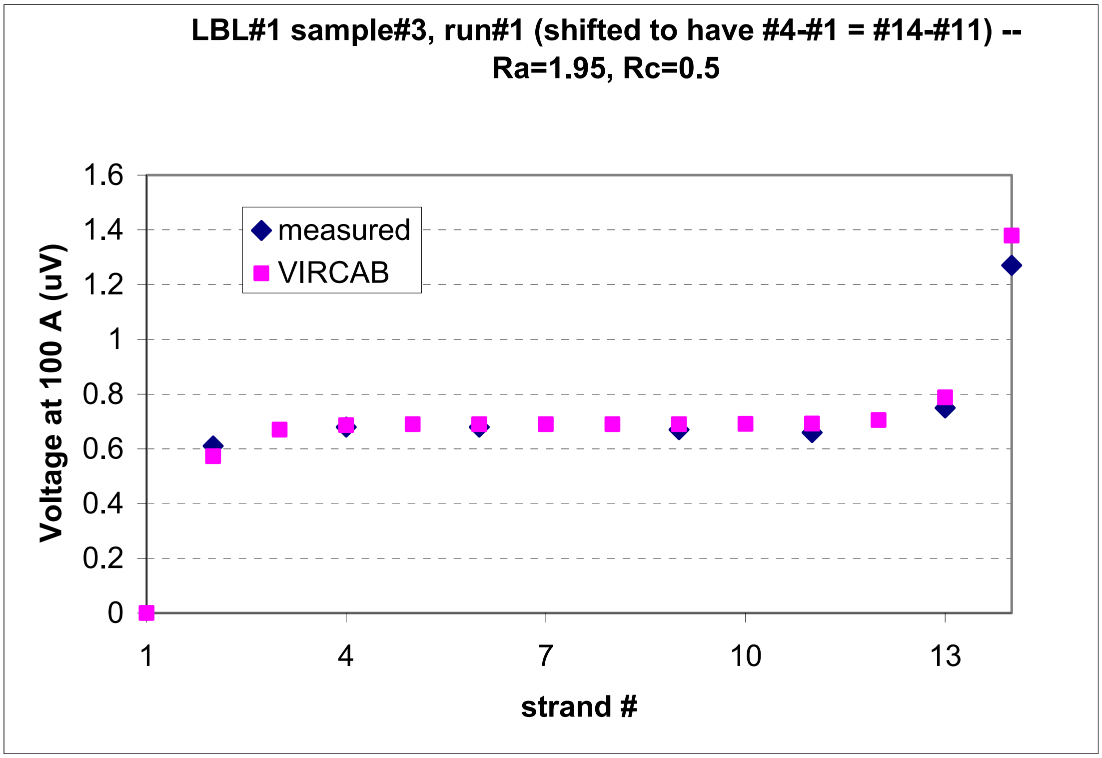

HFDA04-#2pole-1 (Outer) sample#4 -- Ra=4.25, Rc=4.38
measured
VIRCAB
Voltage at 100 A (uV)
strand #
0
1
2
3
4
5
6
7
8
1
4
7
10
13

Table 4: Results and Comparison of the HFDA04-#2 coil

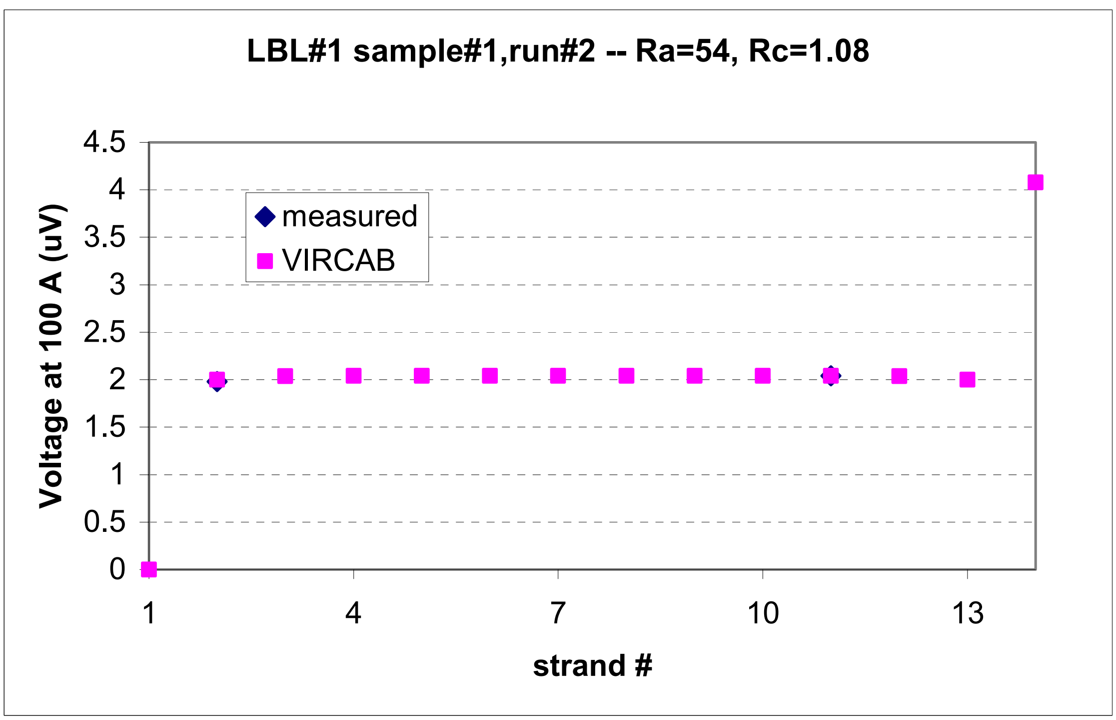
Position	Sample	Coil Layer	Ra (μΩ)	Rc (μΩ)
Midplane	A	Outer	**3**	**30**
	B	Inner	**~3**	**≥ 500**
	C	Inner	**2.6-3**	**≥ 500**
	D	Outer	**2.5**	**20**
Pole-1	2	Inner	**1.88**	**6**
	3	Inner	**0.75**	**4.45**
	4	Outer	**4.25**	**4.38**

LBL#1, Run#1




LBL#1 sample#3, run#1 (shifted to have #4-#1 = #14-#11) -- Ra=1.95, Rc=0.5
Voltage at 100 A (uV)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
measured
VIRCAB
1
4
7
10
13
strand #

LBL#1, Run#2


LBL#1 sample#1,run#2 -- Ra=54, Rc=1.08
Voltage at 100 A (uV)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
measured
VIRCAB
1
4
7
10
13
strand #

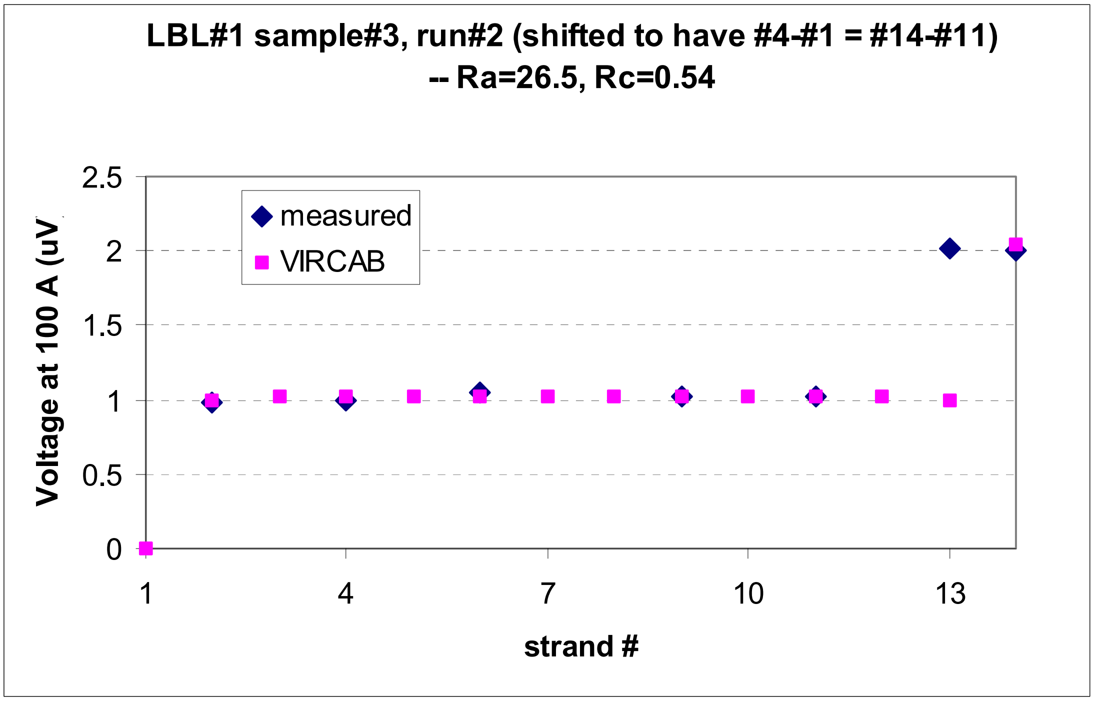


Table 5: Results and Comparison of the LBL Samples

Sample	Run	Ra (μΩ)	Rc (μΩ)
1	1	**20**	**1.2**
	2	**54**	**1.08**
3	1	**1.95**	**.5**
	2	**26.5**	**.54**

Conclusion

The apparatus for the ICR measurements of several samples have been improved by assembling a cart with all of the instruments required including a dedicated PC.
This apparatus have been used to test the turns close to the pole of a sample extracted from HFDA-04 and to compare the results with those of the ICR of turns on the midplane (HFDA-04#2). Those measurements and the comparison gave the following results:

- All cables gave similar values of Ra and Rc.
- Ra on pole-1 turns is similar to the Ra on the midplane turns.
- Rc on pole-1 turns is significantly lower than Rc on the midplane turns.

This apparatus was also used to measure a sample extracted from a common coil magnet fabricated at LBL (RD3A outercoil). These measurements compared to the HFDA-04 results showed the following:

- In LBL#1 Rc is lower than in HFDA-04#2 turns (slightly lower than the pole-1 turn and much lower than the midplane turns).
- In LBL#1 Ra is higher than in HFDA-04#2 turns.

References

[1] CERN Accelerator School. May 1996. *Superconductivity in Particle Accelerators*.
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